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Exploiting Multiple Antennas for Synchronization

Chris Williams, *Member, IEEE*, Stephen McLaughlin, *Senior Member, IEEE*, and Mark A. Beach, *Member, IEEE*

***Abstract*—Orthogonal frequency-division multiplex (OFDM) offers a low-complexity solution to equalization in multipath channels but does so by increasing the symbol period. This places a limit on the mobility of such systems since time variations in the channel during the symbol period introduce intercarrier interference (ICI), hence, degrading performance. Solutions to reduce ICI in the literature require a high degree of processing. Increasing terminal mobility also places greater requirements on synchronization processing to track the rapidly changing channel. This paper uses multiple antennas at the receiver so that the channel response can be decomposed into a number of more slowly varying channels. Independent synchronization processing and correction can be applied to each of the derived channels before combining the signals prior to the fast Fourier transform (FFT) process. By individually processing the channels, the effective channel is compressed in the time and frequency domains, improving system performance. Perfect tracking of the multipath clusters is initially assumed to show the potential benefits, followed by operation with an idealized tracking algorithm. Operation with more realistic processing algorithms using fixed sectored elements improving the bit error rate (BER) is investigated. Finally, the benefits are then demonstrated with real measured channels from an urban environment.**

***Index Terms*—Antenna arrays, digital communications, Digital Video Broadcasting (DVB), orthogonal frequency-division multiplex (OFDM), synchronization.**

I. Introduction

ORTHOGONAL frequency-division multiplex (OFDM) offers a low-complexity solution to equalization in multipath channels but does so by increasing the symbol period. This places a limit on the mobility of such systems since time variations in the channel during the symbol period introduce intercarrier interference (ICI), hence, degrading performance. Solutions to reduce ICI reported in the literature require a significant degree of processing, and increasing terminal mobility also places greater requirements on synchronization processing to track the rapidly changing channel. In this paper, a method is proposed to use multiple antennas at the receiver so that the channel response can be decomposed into a number of more slowly varying channels. Independent synchronization processing and correction can then be applied to each of the derived channels before combining the signals prior to the fast Fourier transform (FFT) process. Previously in the literature, it has been suggested that there would be benefits in slowing the rate of channel variation [1], [2], but there has been no implementation where prior knowledge of channel and/or synchronization parameters was not assumed. The contribution of this paper is to demonstrate the performance improvement in a realistic system without prior knowledge of channel parameters.

In this paper, the terrestrial Digital Video Broadcast (DVB-T) system is used as an example of an OFDM system. In all cases presented, synchronization parameters for timing and frequency are estimated from the received signal. The processes involved can be summarized as follows:

1) separation of the received signal into clusters[1] through spatial discrimination;
2) synchronization parameter estimation per cluster (timing and frequency);
3) synchronization correction;
4) signal combining of the synchronized clusters into a single signal for detection.

In this paper, combining takes place before the OFDM FFT process, and thus, the overall complexity is low. Frequency correction is applied to each cluster before combining, and therefore, the postcombining Doppler spread is bounded by the Doppler spread of each cluster, which is lower than that with a single antenna. The effect of timing correction both before and after the combining process is also investigated.

In this paper, the cases of full and no prior information of the multipath channel spatial characteristics at the receiver are also considered. While, in theory, being able to estimate and track the channel spatial response should ultimately offer significant performance benefits, in practice, errors in the estimation process will degrade performance. A fixed sector approach offers an effective low-complexity solution, and such an approach is proposed here. In addition to the synthetic channels, the effective use of sectored antennas is demonstrated using data measured in an urban channel with a single transmitter.

The results presented here demonstrate that timing correction before combining is generally most effective, but in some cases, a hybrid approach that can switch between precombining timing correction (pre-CTC) and postcombining timing

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[1]In any practical system, the arriving multipath signals will form clusters based on the propagation characteristics of the channel [10]–[15]. In this paper, a cluster is defined as a group of waves with similar delay and angles of arrival in azimuth and elevation, as discussed in [10].

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correction (post-CTC) is better. It is also shown that pre-CTC is effective when the delay spread exceeds the cyclic prefix (CP) length. Therefore, the method of pre-CTC proposed in this paper provides compression of the effective channel in the time and frequency domains (lower delay spread and lower Doppler spread). It is shown that, although energy may be split between multipath clusters, thus lowering the signal-to-noise ratio (SNR) on each channel, the robustness of the synchronization estimator results in no overall loss of performance after signal combination.

This paper is structured as follows: In the next section, details regarding the channel are discussed, followed by a review of possible system architectures for combining synchronization and antenna array processing. Then, brief results are presented for when the channel spatial characteristics are known, followed by results without such prior knowledge using fixed sectors. Finally, conclusions regarding the results are drawn.

II. Channel Characteristics

A. Underlying Channel Model

The considerable interest in multiple-input–multiple-output (MIMO) systems has resulted in a significant number of papers published, which take statistical models and relate them to physical measurements (e.g., see [12]–[14] among others). One characteristic that is consistent in these papers is the presence of temporal and spatial clusters, as discussed in [10] and [12]. These clusters, as discussed in [12], are related to groups of arrivals, which are clustered within a narrow time (200 ms) or an angular (3°–6°) window. This clustering of multipath components has a variety of plausible physical interpretations often related to the geometry of the propagation environment.

The combined impulse response of such channels is described as

$$h(t,\theta)=\sum_{l=0}^{\infty}\sum_{k=0}^{\infty}\left\{\beta_{kl}e^{j\theta_{kl}}\delta(t-T_l-\varepsilon_{kl})\delta(\theta-\theta_l-\omega_{kl})\right\} \quad (1)$$

where T_l and ε_{kl} represent the cluster and ray interarrival times, respectively. That is, T_l is the intercluster arrival time, and ε_{kl} is the intracluster arrival time. Likewise, θ_l and ω_{kl} represent the cluster and ray angle of arrival terms, respectively. The literature discusses suitable distributions for these parameters, and this is discussed later in this paper as the synchronization method is developed.

B. Simulation Channel Model

The channel considered in this paper is based on a nonline-of-sight multipath model proposed by Bug (type UN2 in [3]), which is a standard eight-path tapped-delay filter with Jakes Doppler spectrum on each path (Table I). In the results, moderate and high mobility cases are demonstrated using 100- and 700-Hz Doppler spreads, which correspond to 54 and 378 km/h, respectively, at 2 GHz. The high speed is chosen in consideration of the current high-speed train services that operate in Europe and Japan.

TABLE I
Bug Channel Model UN2 Parameters

Channel	Tap	Delay (μs)	Power (dB)
Bug UN2	1	0	0
	2	0.33	-4.1
	3	0.73	-6.7
	4	1.51	-10.8
	5	2.16	-7.9
	6	2.64	-9.6
	7	3.04	-10.5
	8	3.32	-11.6

The channel model has been extended to a two-transmitter single-frequency network (SFN). The same model is used for both channels, but path variations are independent between channels. Both channels have the same mean power, which is challenging for timing estimation, and the second cluster has a bulk delay of 3 μs (27 samples). This delay, combined with the delay spread on each channel, creates an effective channel that nearly fills the CP with interference from the previous symbol, and thus, accurate timing is required to minimize intersymbol interference (ISI).

From the Bug channel model, the spatial characteristics need to be added. The mean cluster angle for the two clusters is a parameter variable. The angle of each multipath component within a cluster is derived from a random variable with a Laplacian distribution. The Laplacian distribution has been chosen based on the strong evidence in the literature for this being the closest approximation in practice [4], [5], [14], [15], [22]. The mean of the distribution is the cluster mean angle (which is subsequently referred to as the cluster angle), and the variance is a simulation parameter. For simplification, both clusters have the same angular variance. To introduce channel variation, the path angles change at random times, i.e., on average once every 20 symbols, with the Laplacian distribution about the cluster mean angle. In the time domain, the channel is not quasi-static (i.e., it changes smoothly within the symbol), but changes to the path angle are constrained to occur only at the start of the symbol. A spatial channel model with multiple Laplacian-distributed clusters is supported in the literature [5].

Each path has the classical Jakes Doppler spectrum, but the spread is scaled in proportion to the cluster's angular standard deviation ψ_l; thus, narrow clusters will have a lower Doppler spread. Each path has a frequency offset added in relation to its angular position, as shown in Fig. 1, where the cluster index is l, and the ray index is k, which is consistent with (1). In the results that will be presented later in this paper, the direction of motion is 0°.

The motion of a terminal will introduce frequency shifts on the received multipath components (known as Doppler shifts). The most common approach to modeling the Doppler spectrum is to assume that the multipaths arrive with a uniform spatial distribution from all directions. This leads to the typical Jakes spectrum [6]. For other applications not involving terminal motion, a parabolic spectrum may be used [7]. When presented with a signal having a Rayleigh/Ricean Doppler spectrum with a maximum Doppler frequency $F_{d,\max}$, the equalizer will ideally be able to track over the bandwidth of the spectrum,

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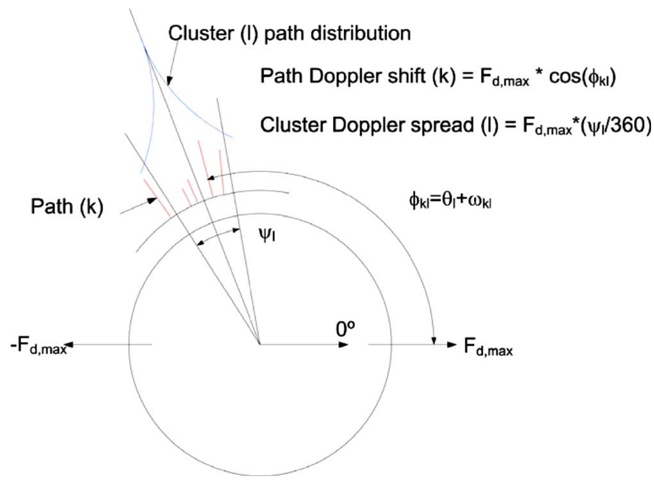

Fig. 1. Spatial modeling of clusters.

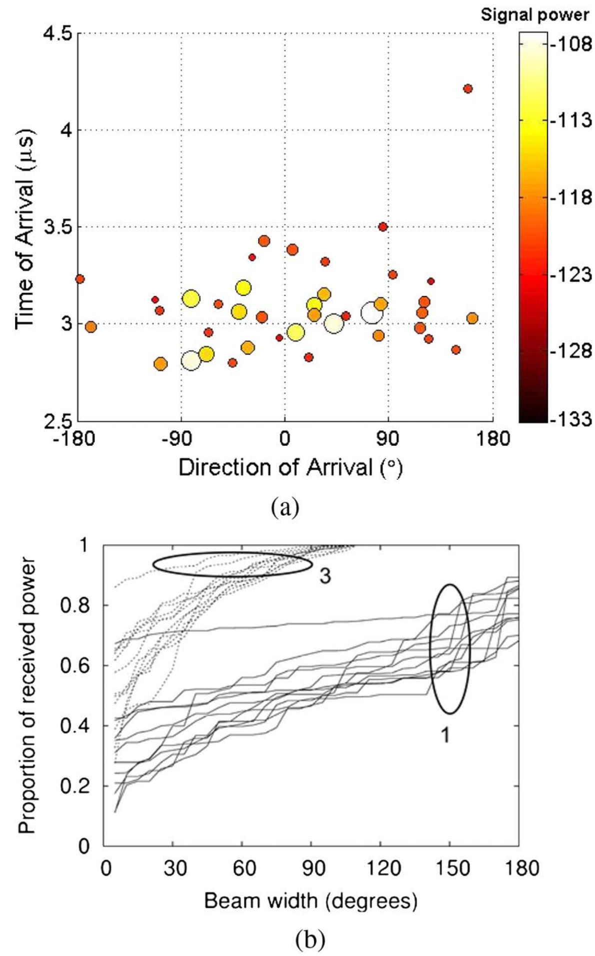

Fig. 2. Urban channel spatial characteristics and power captured with sectored antennas. (a) Shade and size of spots relate to power. (b) (Solid) One-sector and (dotted) three-sector beams.

i.e., $\pm F_{d,\max}$. In OFDM, the Doppler shift and spread in the received signal will introduce ICI between subcarriers. For the DVB-T system investigated in [8] and [9], Doppler spreads greater than 10% of the subcarrier bandwidth degrade performance.

A constant Doppler shift can easily be corrected as part of the pre-FFT synchronization process, but synchronization does nothing for a high Doppler spread.

In practice, the arriving signals will form clusters, as previously discussed in this paper, based on the propagation characteristics of the channel [10]–[15]. A cluster in this paper is defined as a group of waves with similar delay and angles of arrival in azimuth and elevation [10]. In a broadcast system deployed as an SFN [11], signals from different transmitters will be received, and a degree of clustering of multipath components from each transmitter is expected, particularly in suburban or rural environments. In a broadcast SFN, the number of transmitter signals that the terminal can receive may be low and may have a wide angular separation between clusters.

The existence of multipath clusters in single-transmitter systems (e.g., cellular systems) has been demonstrated through a number of measurement campaigns [12], [13]. Less than two or three clusters containing significant power are often seen, with angular spreads less than 20°. With a nonuniform spatial distribution, the Doppler spectrum is not expected to be a typical Jakes spectrum [6]. Based on clustering of scatterers, the Doppler spectrum spread for a single cluster is demonstrated in [14] and [15] to reduce as a function of the angular spread and will have a frequency offset related to the mean cluster angle of arrival.

Even where discrete clusters are not in evidence, it is possible to group the multipath components into clusters, such that a large proportion of the total received power is contained in the union of those clusters. A previous channel measurement campaign has characterized the spatial channel at a mobile terminal in an urban environment [16]. Fig. 2(a) shows one snapshot of the channel characteristics, where each circle corresponds to one multipath component, the position is determined by the path's angle of arrival at the terminal and the path time delay, and the size and shade relate to path strength. In this figure, no clear clusters exist. A search procedure was employed with one or three perfect directional beams (i.e., flat response within the beam and zero response outside), with beam width as a parameter. Fig. 2(b) shows the proportion of energy contained within the optimized beams for different channel snapshots. This demonstrates that only a small number of beams are required to capture most of the energy.

The discussion here has focused on channel clusters seen by the terminal. In cellular systems, the high elevation of the base station (BS) in a macrocell limits the angular spread of the received signal on the uplink [18]. In this situation, a single-frequency correction process would be adequate. There have been some studies that have demonstrated clustering at the BS [18], and the following analysis may also be relevant to these situations.

C. Slowing the Channel

The inability of the equalizer to track the channel and cope with high levels of ICI will limit the mobility of the terminal. To increase the mobility that can be supported, the effective Doppler spread needs to be reduced. This is often referred to as "slowing the channel" in the literature [1], [2].

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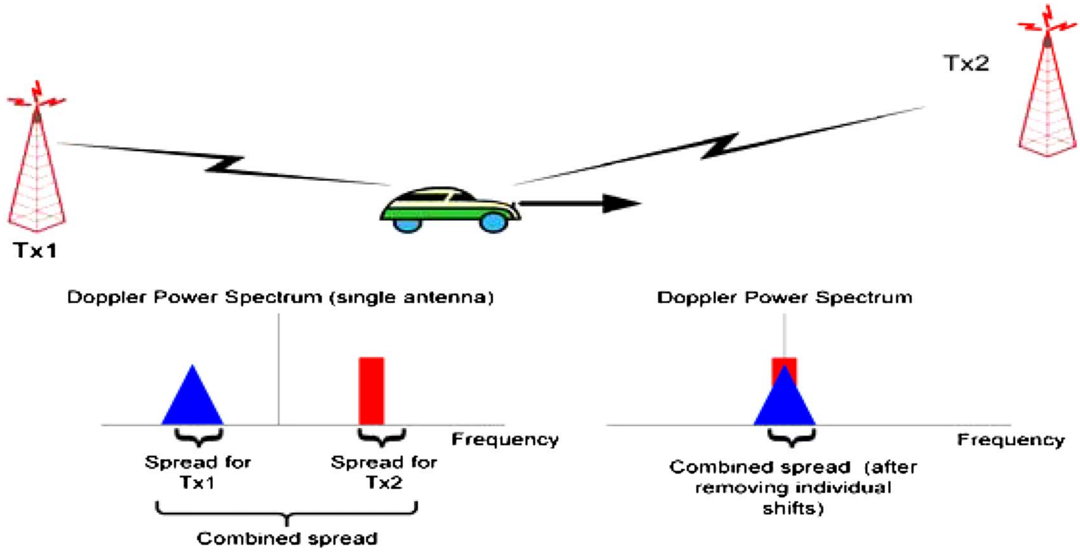

Fig. 3. Reduction of Doppler spread by separation of multipath clusters.

When a single cluster is present, frequency synchronization will remove the frequency offset, leaving a much-reduced Doppler spread. When more than one cluster is present, the spatial separation of the clusters can be used to separate them, and then, individual frequency offset corrections are applied to the individual clusters. This leads to a Doppler spread that is the maximum of the Doppler spreads from the individual clusters. The process is demonstrated in Fig. 3. Since each cluster has a narrow angular spread, the combined Doppler spread is much reduced.

This could be achieved by employing sectored antennas, with each covering a fixed angular range. A design method to determine the angular coverage of each antenna, such that the Doppler spread in each antenna is equal, is described in [1]. However, such an approach requires knowledge of the channel characteristics. In practice, an antenna array could be used to shape beams, but the number of required elements would be large to give sufficient control, and Nørklit and Vaughan [1] note that performance is a little better than that with equal angular partitioning (sectors). Chizhik [2] develops a method of receiver beamforming that is based on the channel estimate (beamforming vector) at each antenna. The ideal processor requires robust channel estimation on each element, and thus, Chizhik proposes to distribute many beams over the expected angles of arrival, although the vector describing the velocity is still assumed to be known.

Both [1] and [2] demonstrate successful slowing of the channel using directional antennas or arrays of antennas; however, knowledge of the channel is assumed, which would require estimation in practice. Inherent in this approach is the use of synchronization processing on each of the derived channels and then the combination of the corrected signals, which, to our knowledge, has not been demonstrated in the literature.

Ng and Dubey [19] take the specific case of OFDM and demonstrate how ICI increases with a higher Doppler spread. A reduction in ICI power is demonstrated when a single directional antenna and (known) frequency offset is employed. This paper does not discuss angular tracking or frequency offset estimation.

A novel idea described in [20] is to introduce apparent movement in the terminals through motion of the antenna, such that the induced directional frequency modulation is sufficient to separate multipath components. Antenna movement can be synthesized by switching (commutating) between array elements. Commutation is required to be sufficiently fast to separate components, and thus, this is likely to work with only a few widely separated paths; otherwise, dense multipath would result in signals becoming smeared.

D. Discussion

The ability to increase the channel coherence time will allow higher mobilities to be supported. In practice, this requires frequency synchronization to be integrated with antenna array processing. For most terminals, only a few antennas can be accommodated, and therefore, processing must be viable for small arrays. While beamforming approaches offer the potential for higher performance, less-complex processing using fixed sectored antennas is likely to be preferred over the rigid array geometry required for beamforming.

Experimental evidence [10]–[15] shows that, temporally, the multipath components within a cluster will have a common timing offset, which could also be removed on a per-cluster basis as part of the synchronization process. Thus, the delay spread will be reduced, further improving performance. Indeed, in some situations, received multipath delay spreads greater than the OFDM CP period could be tolerated. Previous work on timing estimation [8], [9] improved the estimation of FFT window timing, particularly where the first arriving paths were weak. In this situation, the timing point is delayed, and thus, multipath components arriving before this timing point introduce precursor ISI. On the premise that clusters are not only distinct in their Doppler spectrum but also have different delay

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profiles, timing synchronization per spatial cluster could be an effective means to solve precursor ISI. Performance benefits will be achieved where the effective channel response can be compressed in time (lower delay spread) and frequency (lower Doppler spread).

It should be noted that the proposed concept is not reliant on spatial resolution of multipath clusters. Even with a uniform spatial distribution of angles of arrival, partitioning the received signal into sectors would still reduce the rate of channel variation. Where clusters are more tightly focused, greater gains would be achieved. The greatest mobility challenge is likely to arise from high-speed transport, where open terrain is most likely (e.g., high-speed trains as in Europe and Japan), and thus, spatial separation in such environments is reasonable.

A further benefit will be in SFNs, where oscillator accuracy needs to be tightly regulated to ensure that ICI is within acceptable limits. When transmitter signals can be discriminated, and therefore separate frequency offsets applied to each, the regulations on oscillator accuracy could be relaxed.

III. System Architectures

A. System

The exemplar system simulated to illustrate the performance of the method in this paper is based on the DVB-T standard [21] using the 2k mode with a 64-point CP. The occupied bandwidth is 7.6 MHz. The DVB-T simulator includes the pilot and transmission parameter signaling (TPS) structures, as defined in [21], including the appropriate pseudonoise sequences. Channel coding, as defined in [21], has been implemented. The data and TPS information have been produced by random generators. No post-FFT synchronization processing has been included (except equalization), and thus, the assumption has been made that no integer frequency offset exists. The equalizer uses linear Cartesian interpolation between pilots for channel estimation.

The timing estimation used in this paper is based on the correlation-derivative method previously described in [8] and [9]. An outline of the basic algorithm is shown in Table I. Improvement in the performance of this algorithm is possible using the rule heuristics described in [9], which identify possible bad estimates $n_{\rm est}(k)$ and replace them with a more consistent estimate. It should be noted that the purpose of this paper is to combine the synchronization algorithm with spatial processing, and consequently, any alternative synchronization method could be used in practice. Synchronization estimates of timing and frequency offsets are found for each symbol. The estimates were then filtered with a 15-point median and 16-point finite impulse response filters, as described in Table II. The process for reducing the timing estimate variance described in [9] is enabled. All the algorithms investigated in this section use the same frequency estimation technique proposed in [22].

B. Architectures for Joint Synchronization and Channel Processing

Different architectures to integrate synchronization and antenna processing are possible, where synchronization refers to timing and frequency offset compensation. The purpose of antenna processing is to separate the received signal into clusters in the spatial domain, as separation is not possible in the time or frequency domains due to overlap. Synchronization estimation is then applied to each derived cluster, giving timing and frequency offsets for each.

In the absence of additional information, frequency correction is applied per cluster based on the estimate for the given cluster. With timing correction, there are two possible approaches.

1) Per-cluster timing using the estimate for each respective cluster. After correcting the timing on each cluster, the signals are then combined. This approach will be called pre-CTC, as illustrated in Fig. 4. By correcting the timing per cluster, it may be possible to cope with combined delayed spreads that exceed the CP length. This would require that the delay spread within each cluster be constrained to be less than the CP length.
2) The earliest timing estimate across the clusters is applied to all clusters. This approach recognizes that timing estimates could be wrong, and thus, the safest approach would be to choose the earliest estimate (subject to there being sufficient received power in the cluster, for example, in this paper, 10% of the total received power). This approach is termed post-CTC, as illustrated in Fig. 5. The disadvantage of this method will be the additional demands it places on the equalizer. When long timing delays exist, the rate of phase change across the subcarriers is greater, and thus, channel estimation by interpolating between pilots becomes less robust.

Taking $x(t)$ as the transmitted signal over a P path channel with each path j having a combined channel and array processor gain of $a_{i,j}$, Doppler shift of $f_{d,j}$, and delay of τ_j [which is the combination of $T_l + \varepsilon_{kl}$ from (1)], the output from each branch (indexed by i) of the array processor is

$$c_i(t) = \sum_{j=1}^{P} a_{i,j} e^{j2\pi f_{d,j} t} x(t-\tau_j). \tag{2}$$

For the pre-CTC case (Fig. 4), with timing corrections $\tau_{c,i}$ and frequency corrections $f_{c,i}$, the corrected signals are

$$\begin{aligned} y_i(t) &= c_i(t+\tau_{c,i}) \cdot e^{-j2\pi(f_{c,i})t} \\ &= \sum_{j=1}^{P} a_{i,j} e^{j2\pi(f_{d,j}-f_{c,i})t} x(t-\tau_j+\tau_{c,i}). \end{aligned} \tag{3}$$

After combining M branches, each corresponding to a cluster, with weight w_i, the single-channel input to the detector is

$$z(t) = \sum_{i=1}^{M} w_i \sum_{j=1}^{P} a_{i,j} e^{j2\pi(f_{d,j}-f_{c,i})t} x(t-\tau_j+\tau_{c,i}). \tag{4}$$

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TABLE II
SYNCHRONIZATION ALGORITHM [9]

Define: Sample interval, T; sample number, n; symbol number, k; OFDM symbol length, N_S; OFDM guard samples, N_g; received signal, $r(kN_S+nT)$.	
Self-correlate received signal	$\gamma(kN_S+nT)=\sum_{i=0}^{N_g-1} r(kN_S+nT)r^*(kN_S+nT+iT))$
1 point differentiate	$d(kN_S+nT)=\gamma(kN_S+nT)-\gamma(kN_S+(n-1)T)$
Average differentiation	$b(kN_S+nT)=\sum_{i=0}^{N_g/2} d(kN_S+(n-i)T)$
Peak search	$p(kN_S)=\max_{0\le i<N_S}\{b(kN_S+(n+i)T)\}$ Time at peak $=n_P$
Choose points (within T_1 and T_2 of $p(kN_S)$, and after peak)	$b(kN_S+nT)\in\beta(k)$ if $T_1<b(kN_S+nT)<T_2$ and $(kN_S+nT)>n_P(kN_S)$ Fit $b=A+Bn$, for $s(n)\in\beta(k)$
Approximated Least squares (LS) fit of points between the thresholds	$A=\frac{4}{N}\sum_{n=0}^{N-1}s[n]-\frac{6}{N^2}\sum_{n=0}^{N-1}ns[n]$ $B=\frac{12}{N^3}\sum_{n=0}^{N-1}ns[n]-\frac{6}{N^2}\sum_{n=0}^{N-1}s[n]$
Estimated timing point, where LS fit takes value of peak	$n_{est}(k)=\frac{p(k)-A}{B}$
Median filter previous estimates, over L_M points	$m(k)=median\{n_{est}(k)..n_{est}(k-L_M)\}$
Average estimates over L_A points to give final estimate	$s(k)=\sum_{l=0}^{L_A-1}m(k-l)$

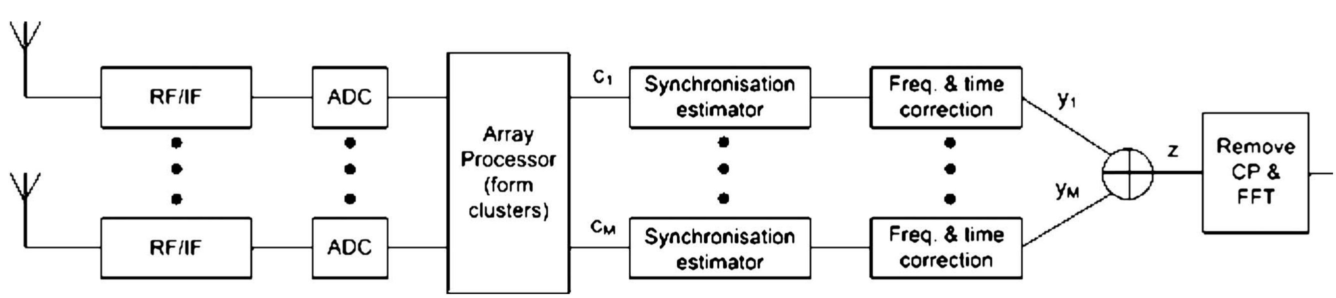

Fig. 4. Architecture for pre-CTC.

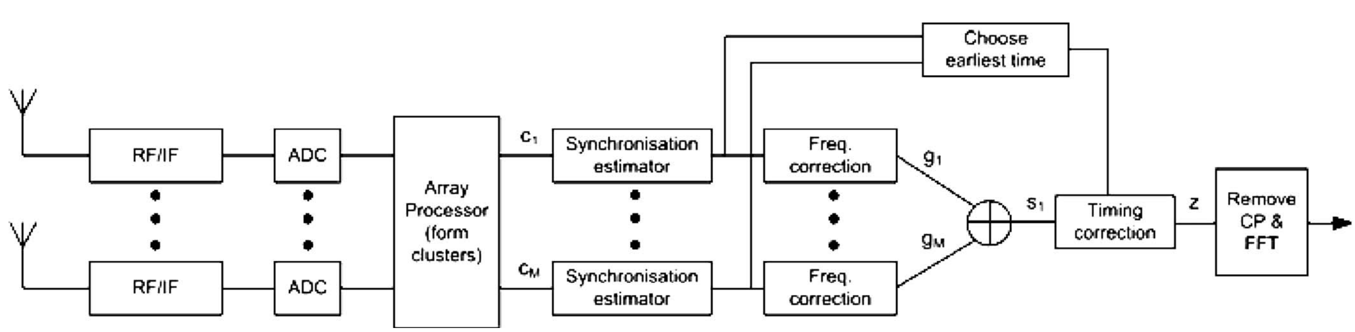

Fig. 5. Architecture for post-CTC.

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For post-CTC, the timing correction is taken as $\tau_{c,\min} = \min\{\tau_{c,i}\}$, and hence, the input to the detector is

$$z(t) = \sum_{i=1}^{M} w_i \sum_{j=1}^{P} a_{i,j} e^{j2\pi(f_{d,j}-f_{c,i})t} x(t - \tau_j + \tau_{c,\min}). \quad (5)$$

In both cases represented in Figs. 3 and 4, the signals are additively combined, with the weight w_i proportional to the received power in that cluster. This was found to offer better performance than equal weight combining.

C. Antenna Characteristics and Processing

The key process in the system is the separation of the received signal into clusters. As already described, the separation of clusters in the time or frequency domain is not possible. Therefore, separation is carried out in the spatial domain. To be effective, a good degree of discrimination is desirable; however this could require many antenna elements, and consequently, there exists a tradeoff between complexity and discrimination. For mobile terminals, the ability to support multiple antennas is limited, and thus, this paper has limited the number for consideration to be typically less than four.

Two aspects need to be considered: 1) the characteristics of the individual elements and the array parameters (location and orientation) and 2) the method of separation of clusters given the signals from each antenna.

Sectored antennas offer a low-cost solution since no array processing is required. However, without any tracking mechanism, any true spatial clusters would not be guaranteed to be centered within a sector and may actually straddle two sectors. This is called cluster splitting. Clusters straddling sectors will share energy between the sectors, and thus, the SNR will be degraded. When recombined, the original SNR will be recovered, but synchronization estimates could be degraded if the SNR drops too low in a given sector. Fortunately, as shown in [9], the SNR performance of the synchronization algorithms is more robust than the detector, and thus, some cluster splitting is tolerable. There is also the possibility of two clusters existing at opposite extremes of the sector, and thus, synchronization would again be degraded. With more sectors, better separation of clusters is possible, but the chances of cluster splitting are increased. Antenna elements forming sectors can have a good front-to-back ratio, and thus, rejection of out-of-sector clusters would be good. With perfect synchronization, it is expected that slowing of channel would be at least proportional to the number of sectors or better, depending on the cluster angular spread. It is possible to apply some overlap of sectors to reduce cluster splitting, but slowing of the channel would not be as effective.

It may appear better to form tracking beams, such as with beamforming approaches. The most flexible approach is with omnidirectional antennas, but this is a less practical solution. Separation between clusters relies on processing gain, which would be limited with only a few elements. Many array processing algorithms have been proposed in the literature. A problem in this scenario is that the received signals will all be correlated, which causes some algorithms to fail. Further processing can be employed to address such correlation, but the complexity will be even higher. Beamforming algorithms also rely on accurately knowing the array vector, and any errors in the vector would degrade performance.

IV. Perfect Knowledge and Idealized Tracking

In the ideal case, the spatial channel characteristics would be known, and the beams could be aligned to maximize performance. Two approaches are investigated in this section to determine what performance is possible assuming perfect channel knowledge.

1) The mean angle of arrival of each cluster is known, and therefore, the beams are aligned along those directions. For each simulation, the beam alignments are held fixed (since the mean angle of the clusters does not move, only the instantaneous angle of the paths is used).
2) The angle of arrival and power of each path are known, and for a given beam width, all alignments are searched (with 15° quantization) to maximize the total received power. Optimization is continuously applied, and thus, the alignments will track the channel variations during the simulation.

Idealized beams have been used, and a system with only two beams has been considered in this paper. They are perfectly attenuated outside the specified beam width and have a raised cosine shape within the beam $(\text{gain} = 0.9 + 0.1\ \cos(\theta))$, which helps the tracking algorithm without significantly affecting performance. The search algorithm initially searches to find the maximum received power. Where a number of angles give the same proportion of received power, the combination that most equally balances the power between the two beams is chosen. This prevents the situation where one beam is sufficient to catch all the received signals and the other contains none.

A. Two-Cluster Channel

Here, the performance of the two beam alignment methods just described is investigated. The previously described two-cluster channel model is used. The timing estimation results show the mean timing estimate (in samples), where zero is the first arriving multipath component, and 27 samples is the delay of the second multipath cluster due to the 3-μs delay previously described.

1) Impact of Beam Width: The system performance with two angular configurations of the clusters is shown in Fig. 6. In addition to the bit-error-rate (BER) performance, the mean synchronization timing estimates (in samples) are demonstrated for each of the cluster channels (Figs. 4 and 5), where for the two-cluster model, we expect to see estimates at 0 and 27 sample offsets, as described earlier in this paper. With a wide angular separation [Fig. 6(c)], the superiority of the

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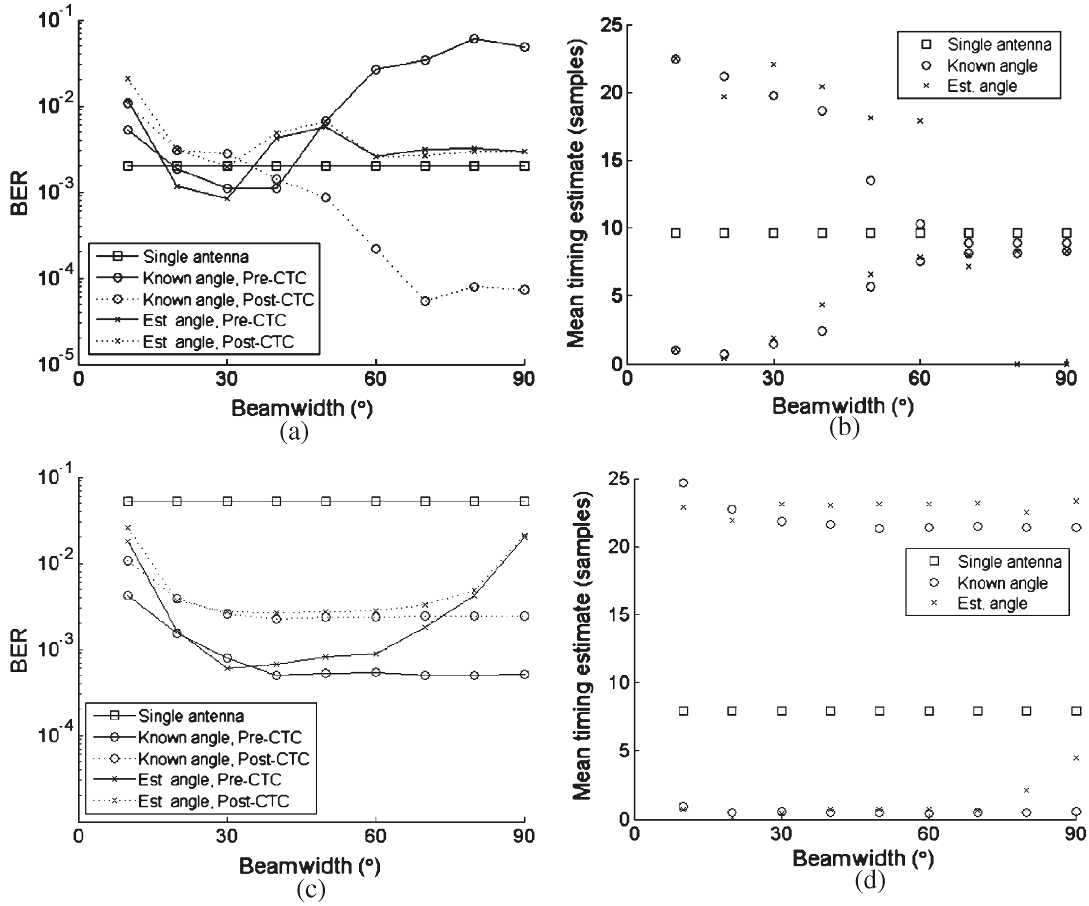

Fig. 6. Impact of beam width with known channels (700-Hz Doppler, $E_b/N_0 = 16$ dB). (a) BER, cluster angles 20° and 45°. (b) Timing estimates, cluster angles 20° and 45°. (c) BER, cluster angles 20° and 90°. (d) Timing estimates, cluster angles 20° and 90°.

beam-steering approach over a single antenna is clear. The separation of the timing synchronization estimates is demonstrated, where the beam width is sufficiently narrow, but for wide beam widths and/or close cluster angles of arrival, the estimates converge to a single estimate [Fig. 6(b)]. The figures demonstrate how performance is closely related to the ability to separate the synchronization parameters between clusters. Performance gains are also achieved at low Doppler spreads by separating the cluster timing estimates.

Comparing the two timing correction architectures, in most situations, the pre-CTC method performs better than the post-CTC method. A notable exception is for known mean angle of arrival, and with the clusters close together, where the performance of pre-CTC becomes very poor [Fig. 6(a)]. This will be discussed in more detail in the next section. Excluding this case, the fixed (known mean) cluster alignment method performs better than the tracking method. Both cases show performance degradation when the beam width is too narrow due to loss of received power. At wider beam widths and where overlap between clusters exists (such as with clusters at 20° and 90°), nonoptimum pointing of the tracking method also degrades performance.

2) Impact of Cluster Separation: Fig. 7 shows the system performance where the angle of arrival of one cluster is variable. As before, the pre-CTC method typically outperforms the post-CTC method, and the tracking method converges to the case with known mean angle of arrival for wide angular separations.

Of note is the unusual behavior at low angles of arrival where the mean arrival angle is known. This is a result of the combining process. When the timing offset is on the order of one sample between the two clusters, and when the signals on the two antennas are nearly identical (that is, when the angles of arrival are close), the phase differences of the symbols from each cluster at the outer subcarriers are approximately out of phase, and thus, they will destructively combine. Since the destructive interference affects a large number of adjacent symbols, including pilots, the BER increases more than if the affected symbols were more widely distributed. The tracking algorithm does not see the same behavior since the offset between the beams ensures that the signals are sufficiently different, and therefore, their timing estimates for destructive combining are not a significant issue.

A solution to this problem, if it were to occur in practice, would be to adopt a hybrid timing correction approach. Where two beams have similar angles of arrival, the timing offsets in each could be compared. If greater than a threshold, then a pre-CTC approach could be used; otherwise, post-CTC (i.e., take the earliest timing estimate and apply to both beams) would be used.

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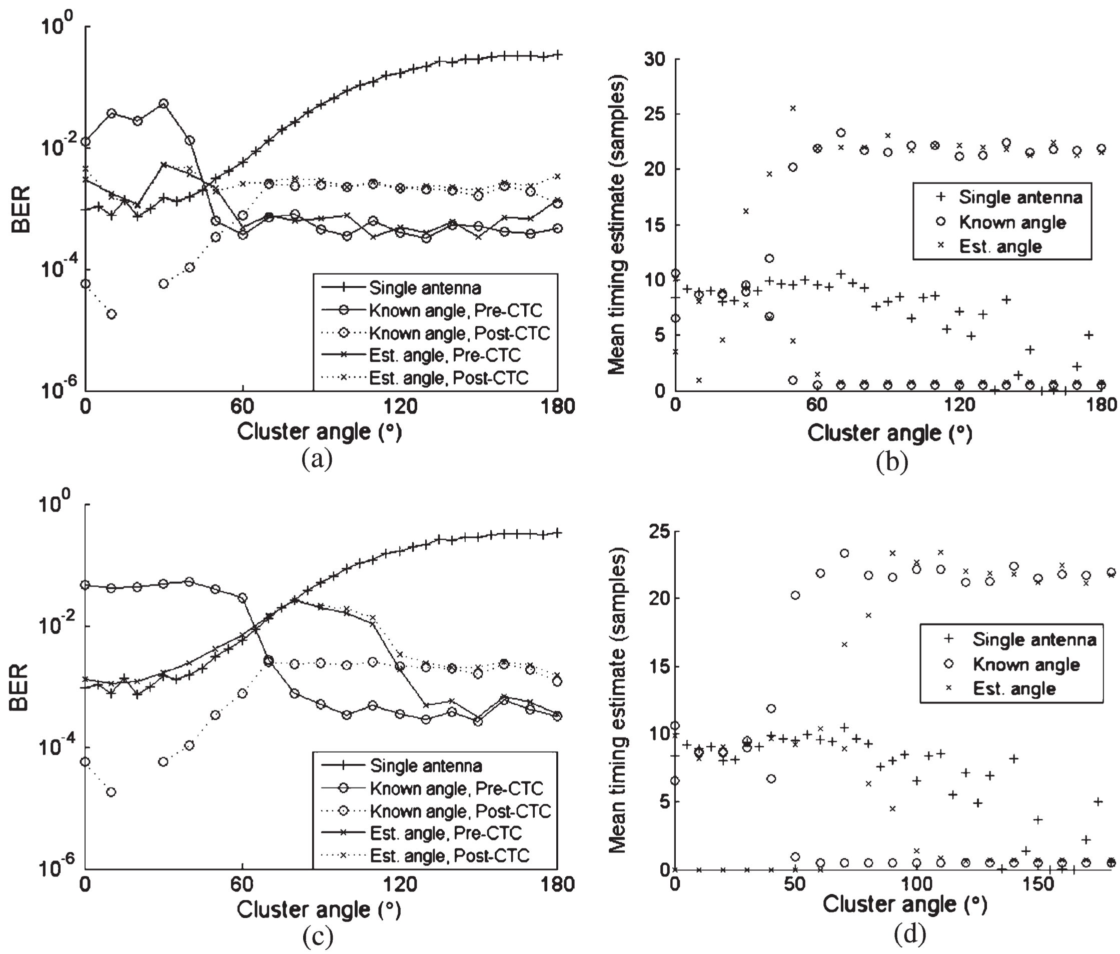

Fig. 7. Impact of cluster angular separation with known channels (700-Hz Doppler, $E_b/N_0 = 16$ dB). (a) BER, fixed cluster at 20°, beam width 45°. (b) Timing estimates, fixed cluster at 20°, beam width 45°. (c) BER, fixed cluster at 20°, beam width 90°. (d) Timing estimates, fixed cluster at 20°, beam width 90°.

3) Mobility Performance: Finally, performance is compared as a function of Doppler spread (as seen through a single antenna) in the figure. This shows that the degradation of performance with higher mobility is much reduced when cluster separation is employed. For the single-antenna system, the BER is approximately 10^{-3} up to 100–200 Hz and then rapidly increases. Depending on the cluster spatial properties (separation and spread), the BER can be less than 10^{-3} up to and beyond 1000 Hz [see Fig. 8(a) and (b)]. With 45° beam widths, in the ideal case, slowing of the channel by a factor of 8 would be expected, and thus, the extra gains are a consequence of improved timing synchronization.

The synchronization frequency estimates in Fig. 8(c) and (d) clearly identify the offsets in each cluster linearly rising with the Doppler rate, whereas the single-antenna case only provides a single estimate that is somewhere between the offsets for the two clusters.

B. Summary and Discussion

The results presented earlier in this paper demonstrate how the performance of the system is closely related to the ability to separate the synchronization parameters between clusters. Performance gains are also achieved at low Doppler spreads by separating the cluster timing estimates. Performance will depend on the relationship between the cluster parameters and the beams used. Narrow beams will lower the Doppler spread, but if too narrow, then cluster energy will be lost, thus lowering the SNR (impacting estimation performance). Wider beams are less prone to cluster splitting if tracking is adequate, but where clusters are not widely spaced, or clustering is weak, then the received angular spread will be high, and therefore, the Doppler spread will also be high.

Pre-CTC proved to be most effective except when the derived clusters were strongly correlated and had a small timing offset difference between clusters. If such a situation is detected, then a hybrid timing correction method can be employed. Pre-CTC can also be used when the delay spread exceeds the CP length on the condition that channel clustering is present.

V. Realistic Approaches

The previous section used ideal knowledge of the channel to align perfect spatial beams. Clearly, such knowledge is not available at the receiver, and alternative strategies must be employed. In this section, a fixed sector pattern is used without using or estimating any channel parameters. The analysis is based on idealized two cluster channels. To demonstrate the

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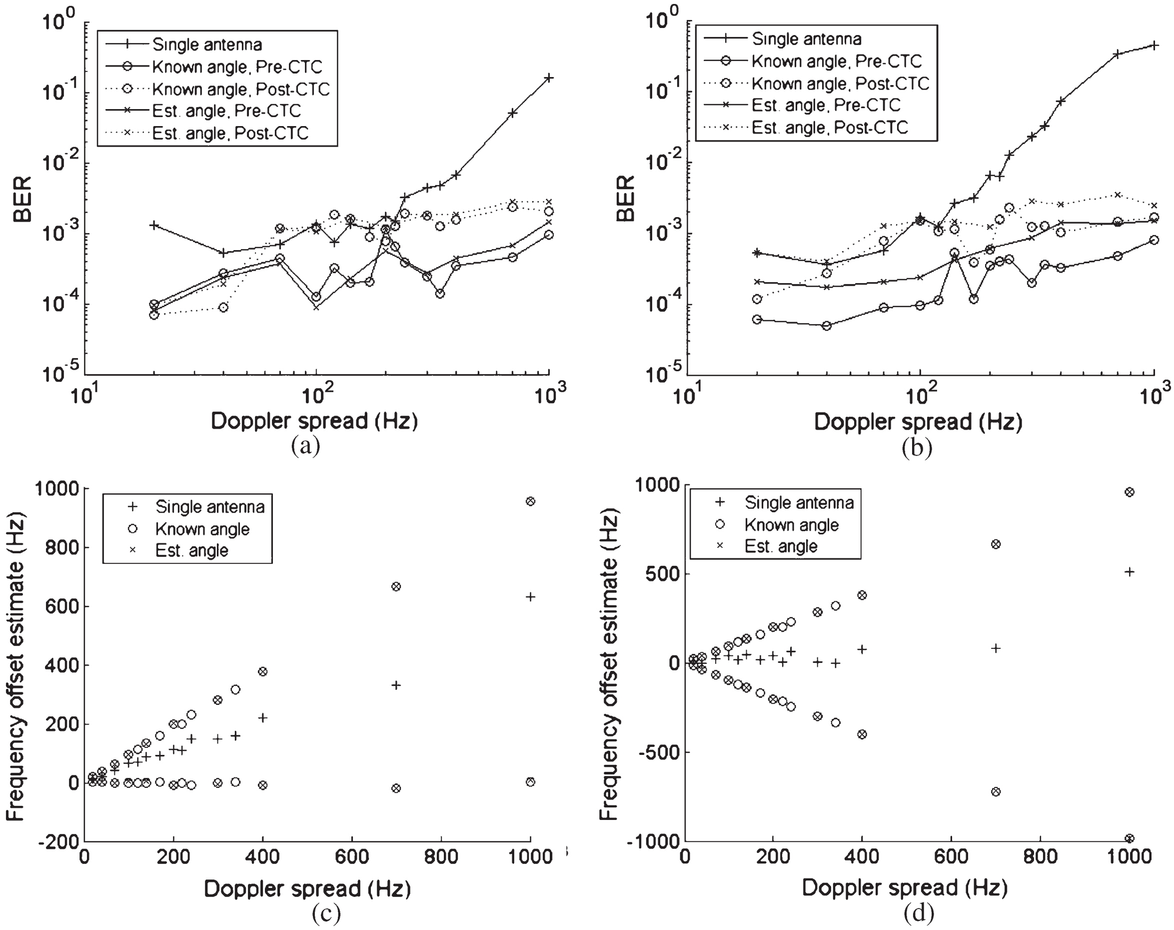

Fig. 8. Mobility performance with known channels ($E_b/N_0 = 16$ dB). (a) BER, cluster angles 20° and 90°, beam width 45°. (b) BER, cluster angles 20° and 180°, beam width 45°. (c) Frequency offset estimates, cluster angles 20° and 90°, beam width 45°. (d) Frequency offset estimates, cluster angles 20° and 180°, beam width 45°.

benefits of incorporating multiple antennas within synchronization processing, a performance assessment based on measured urban channels is subsequently presented, followed by a discussion of the results from this section.

A. Two-Cluster Channel With Sectors

1) Method Description: In the absence of channel information, the channel dynamics can be slowed by splitting the incoming signals into equal sectors. With a uniform distribution of angles of arrival, the channel should be slowed (i.e., the Doppler spread reduced) by a factor equal to the number of (equal-sized nonoverlapping) sectors. Where the multipath clusters have narrower angular spreads, then the reduction will be greater as long as each sector contains only one cluster.

It is possible that a cluster may be split between two sectors. With only a single cluster present in a sector, this will provide a degraded SNR to synchronization processing, and thus, synchronization estimates could be degraded and will impact on system performance. Where multipath components from multiple clusters occur in a sector, then synchronization estimates are likely to be further degraded since time and frequency offsets will be different between clusters (by definition).

A solution is to overlap sectors to try to reduce the likelihood of cluster splitting. Consequently, this will increase the likelihood of a cluster falling entirely within one sector, and thus, at least one sector would have most of the energy from that cluster. However, wider sectors will also increase the likelihood of more than one cluster being present in a sector, thus degrading synchronization performance and reducing the slowing down effect of the channel. In practice, a degree of overlap between sectors is to be expected by design or otherwise.

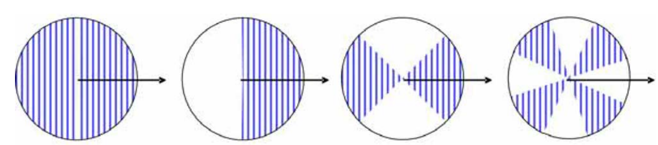

Fig. 9. Sector orientations. The 0° reference is denoted by the arrow.

In this section, the sectors are oriented such that one is bisected by the 0° reference, as shown in Fig. 9. As before, a two-cluster channel model is adopted, with an angular standard deviation of 45° about the mean cluster position. In later sections, the number of sectors is denoted by the symbol A.

2) Impact of Cluster Separation: With two clusters close together [Fig. 10(a)], only the eight-sector system shows any improvement. With wider angular separations, the benefits of four and two sectors are demonstrated in Fig. 10(b) and (c). The pre-CTC method offers the best performance.

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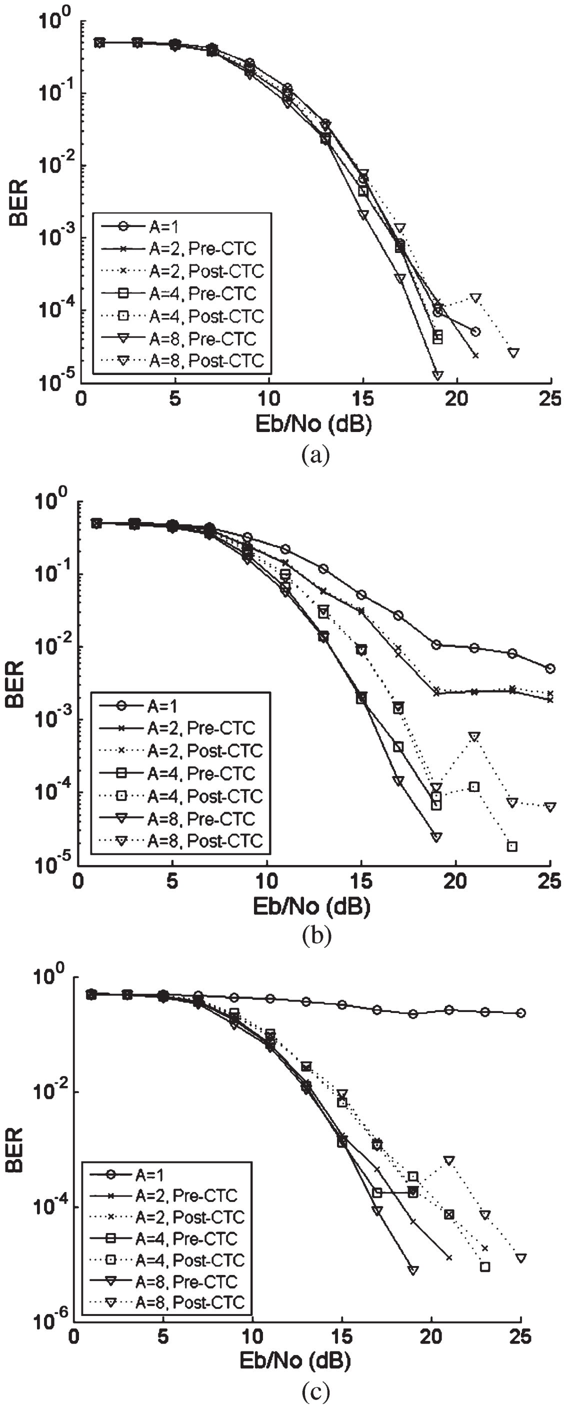

Fig. 10. BER performance for sectors. (a) BER, clusters at 20° and 45°. (b) BER, clusters at 20° and 90°. (c) BER, clusters at 20° and 180°.

With a low level of Doppler spread, Fig. 11(a) shows the effect of cluster splitting on the eight-sector system (sector boundaries are obvious at approximately 67.5°, 112.5°, and 157.5°). The impact of adding 10% overlap is shown in Fig. 11(b). For pre-CTC, the peaks are reduced for wide cluster angular separations. The benefit for post-CTC is more substantial, and now, the difference between the two methods is less significant. Of note is how, at low angular separations, the post-CTC method now offers better performance.

Increasing the Doppler rate in Fig. 11(c) shows the clear benefit of using sectors. With only two sectors, when the variable cluster is near, the boundary performance is degraded due to the larger effective Doppler spread and less-effective Doppler estimation/correction. An overlap improves the performance of the post-CTC method [Fig. 11(d)]. There are two effects happening here. The overlap improves the frequency estimation performance, which is the dominant effect for post-CTC between 60° and 90°. The second effect is that the timing estimates between 80° and 120° are more delayed with sector overlap in both sectors. This extra delay introduces ISI, and thus, performance is degraded. The performance of the pre-CTC method is dominated by this delay, and thus, performance is degraded with offset for all angles. The adverse effects of the timing delay between 100° and 120° dominates in the post-CTC method.

3) Mobility Performance: Even with close angular separation, Fig. 12 shows the benefit of multiple antennas. For close angular separation, the ability to separate timing estimates between clusters is the dominant factor; indeed, Fig. 12(a) shows that with eight sectors and using post-CTC (a single timing estimate for all sectors), performance is degraded. With wider angular separations, the benefits relating to individual frequency offset corrections dominate. Again, pre-CTC offers the best performance.

4) Overcoming Long Delay Spreads: It was previously suggested that separating the signal into clusters will help provide adequate system performance, even when the delay spread is larger than the CP interval. When the clusters are well defined and there is no cluster splitting [Fig. 13(b)], performance is nearly independent of the delay between clusters. However, if the delay becomes too large, then the delayed cluster may get confused as a pre-echo of the next symbol, and thus, associating the output from each sector to the correct symbol will require additional processing.

When cluster splitting does occur (as it does to a small degree in Fig. 13(a) due to the closeness of the clusters), then performance is limited by the overlapping cluster "pulling" the timing estimate away from its true position, and the effective delay spread increases. As clusters become closer, this pulling will have a greater effect, until eventually, the clusters are not separable to the degree required.

B. Sectors in an Urban Channel

The analysis so far has been based on an idealized two-cluster channel model. This section presents results based on the previously discussed urban channel measurements (see Fig. 2). From this measurement set, a number of snapshots of the channel have been taken and used in the DVB-T system simulation described in this paper with four sectors and pre-CTC. For each simulation, the angles of arrival and mean power of each path are fixed. A fixed frequency offset is applied to each path based on its angle of arrival and maximum Doppler frequency, but an additional slow (40 Hz) Doppler spread variation is applied to give statistical averaging. The effect of the channel will depend on the direction of motion. For the single-antenna case, three directions of motion have

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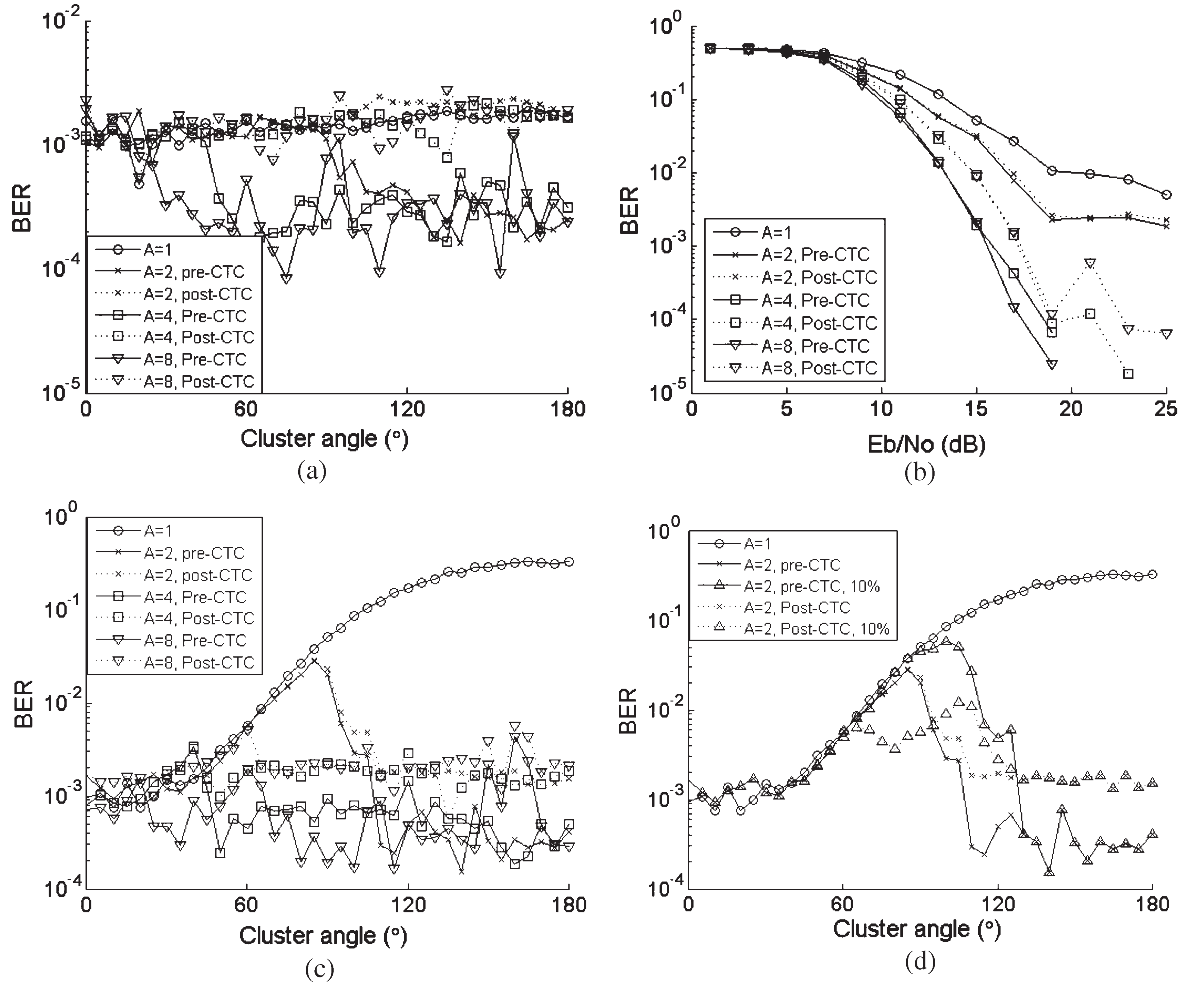

Fig. 11. Impact of cluster angular separation and overlap with sectors $(E_b/N_0 = 16 \text{ dB})$. (a) BER, fixed cluster at 20°, 100 Hz, no overlap. (b) BER, fixed cluster at 20°, 100 Hz, 10% overlap, eight sectors. (c) BER, fixed cluster at 20°, 700 Hz, no overlap. (d) BER, fixed cluster at 20°, 700 Hz, 10% overlap, two sectors.

been simulated (0° and ±45°). With four sectors, only two directions are presented since the results for +45° and −45° are identical due to symmetry.

Fig. 14 demonstrates that for the cases shown, performance benefits are achieved in all cases, even at low Doppler frequencies (due to the compression of the effective channel in the time domain). Fig. 14(b) also includes the case where the previously presented tracking algorithm has been used. A small improvement in performance over the fixed sector system can be observed.

C. Discussion

This section has demonstrated that even a nontracking approach to combining multiantenna processing and synchronization can provide performance advantages. As expected, the greater resolving ability of more sectors often leads to higher performance, but cluster splitting can become an issue, and sector overlap appears to help in this regard. A four-sector system would appear to offer a good compromise between performance and complexity.

In common with the tracking results, pre-CTC typically provides the best performance, although with sector overlap, this is not always the case. It was also shown that the pre-CTC method may allow very long delay spreads to be tolerated if spatial separation provides a reduction in the delay spread in each sector.

An alternative approach that is not considered here would be to have more sectors than required, with significant overlap, and to choose a subset to give the gains of narrow sectors but avoid cluster splitting.

The sectored approach has also been demonstrated to be effective, even in simulations using measurements from a real urban channel, and little was lost compared with a tracking method with perfect channel knowledge.

A practical implementation of tracking using beamforming has also been investigated but is not reported here. With omnidirectional elements, and with only a few elements, a poor front-to-back ratio of the synthesized beams meant that separation of clusters was limited, and performance was therefore poor. By reducing beam widths to 10% overlap (i.e., four sectors of 108°) and with a close antenna separation (0.2 wavelengths), improved performance was achieved in most cases. With this 10% overlap configuration, the system was virtually running as a sectored system, and performance was similar between the two systems. Therefore, the additional complexity of the beamforming approach was not justified.

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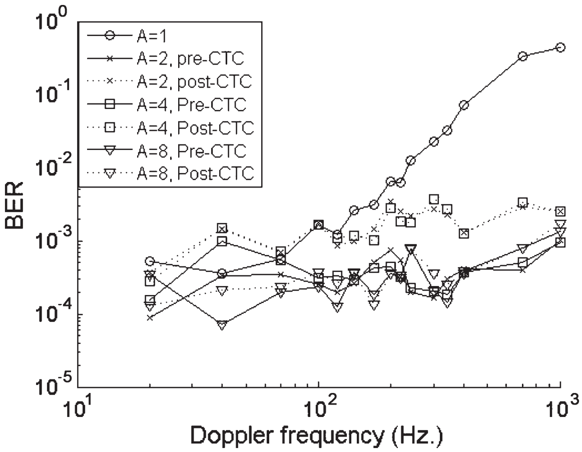
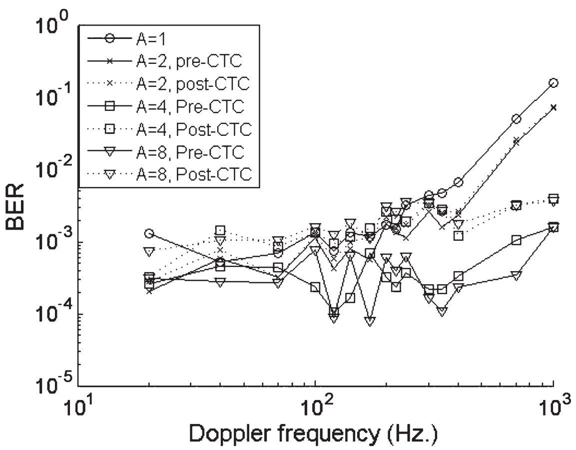
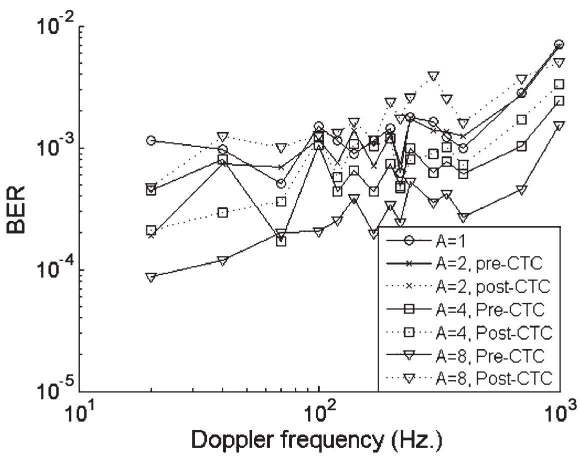


(a)

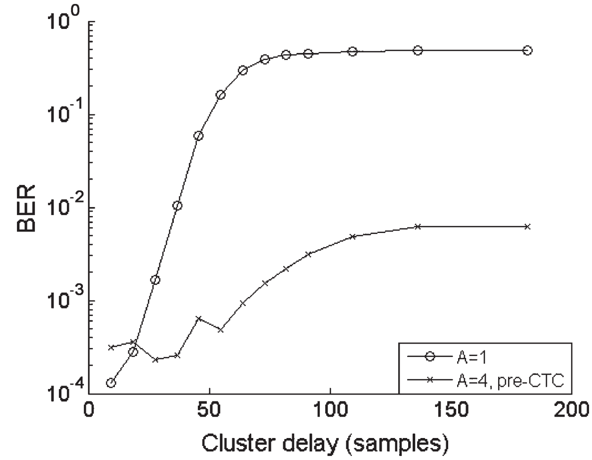


(b)

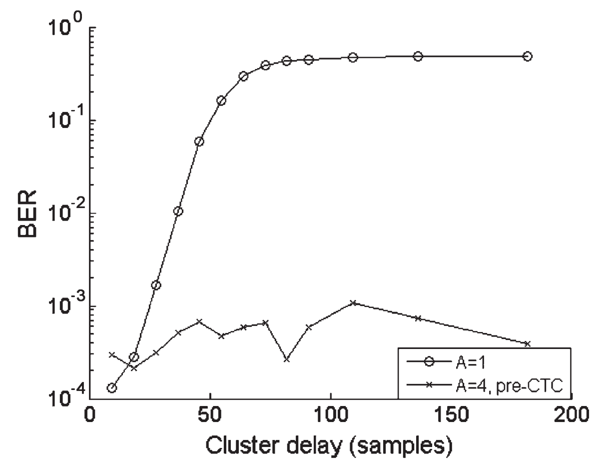


(c)

Fig. 12. Mobility performance for sectors ($E_b/N_0 = 16$ dB). (a) BER, cluster angles 20° and 45°. (b) BER, cluster angles 20° and 90°. (c) BER, cluster angles 20° and 180°.



(a)



(b)

Fig. 13. Long delay spreads with sectors ($E_b/N_0 = 16$ dB). (a) BER, cluster angles 20° and 90°. (b) BER, cluster angles 20° and 180°.

VI. Conclusion

This paper has presented results demonstrating the advantages of integrating multiple-antenna processing with frequency and timing synchronization. While, in theory, being able to estimate and track the channel spatial response should give performance benefits, in practice, errors in the estimation process degrade performance, and it was shown that a fixed sector approach offers an effective low-complexity solution. Indeed, even if perfect knowledge of the channel characteristics was available, obtaining an optimum selection of the array and synchronization parameters is not currently possible due to the complex interaction between the FFT and equalization processing. Further degradation can also occur because of uncontrolled sidelobes, which do not allow effective cluster separation. Thus, the improved front-to-back isolation of sectored elements offers better performance.

Timing correction before combining is generally most effective, but in some cases, a hybrid approach that can switch between pre- and post-CTC methods was demonstrated to be effective. Pre-CTC was also demonstrated to be effective when the delay spread exceeds the CP length. Therefore, the proposed method of pre-CTC provides compression of the effective channel in the time and frequency domains (lower delay spread and lower Doppler spread). Although energy may be split between clusters, lowering the SNR on each channel, the robustness of the synchronization estimator results in no overall loss of performance after signal combination. In addition to the synthetic channels, the effective use of sectored antennas has also been demonstrated in a real urban channel.

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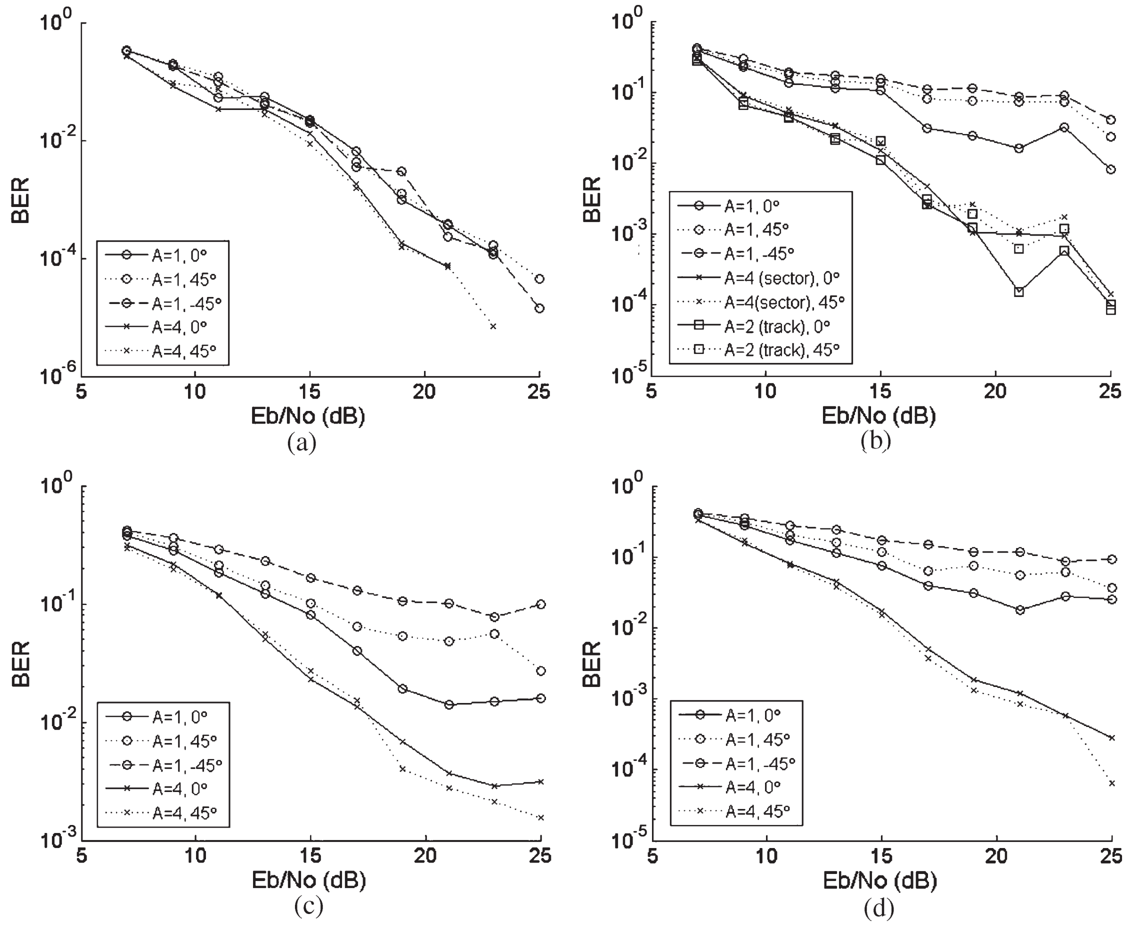

Fig. 14. Performance of a sectored system in a real urban channel. (a) BER, channel 1, 100 Hz. (b) BER, channel 1, 700 Hz. (c) BER, channel 2, 700 Hz. (d) BER, channel 3, 700 Hz.

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REFERENCES

[1] O. Nørklit and R. G. Vaughan, "Angular partitioning to yield equal Doppler contributions," *IEEE Trans. Veh. Technol.*, vol. 48, no. 5, pp. 1437–1442, Sep. 1999.

[2] D. Chizhik, "Slowing the time-fluctuating MIMO channel by beam forming," *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, pp. 1554–1565, Sep. 2004.

[3] S. Bug, C. Wengerter, I. Gaspard, and R. Jakoby, "WSSUS—Channel models for broadband mobile communication systems," in *Proc. IEEE VTC—Spring*, May 2002, vol. 2, pp. 894–898.

[4] K. Pedersen, P. E. Mogensen, and B. H. Fleury, "Power azimuth spectrum in outdoor environments," *Electron. Lett.*, vol. 33, no. 18, pp. 1583–1584, Aug. 1997.

[5] C.-C. Chong, C.-M. Tan, D. I. Laurenson, S. McLaughlin, M. A. Beach, and R. Nix, "A new statistical wideband spatio-temporal channel model for 5-GHz band WLAN systems," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 2, pp. 139–150, Feb. 2003.

[6] W. C. Jakes, *Microwave Mobile Communications*. Hoboken, NJ: Wiley, 1974.

[7] *Air Interface for Fixed Broadband Wireless Access Systems*, IEEE Std. 802.16-2004, 2004.

[8] C. Williams, M. A. Beach, and S. McLaughlin, "Robust OFDM timing synchronisation," *Electron. Lett.*, vol. 41, no. 13, pp. 751–752, Jun. 23, 2005.

[9] C. Williams, S. McLaughlin, and M. A. Beach, "Robust OFDM timing synchronisation," in *Proc. IEEE VTC—Spring*, Melbourne, Australia, May 2006, pp. 1947–1950.

[10] H. Asplund, A. F. Molisch, M. Steinbauer, and N. B. Mehta, "Clustering of scatterers in mobile radio channels—Evaluation and modeling in the COST259 Directional Channel Model," in *Proc. ICC*, 2002, vol. 2, pp. 901–905.

[11] P. Shelswell, "The COFDM modulation system: the heart of digital audio broadcasting," *Electron. Commun. Eng. J.*, vol. 7, no. 3, pp. 127–136, Jun. 1995.

[12] L. Vuokkol, P. Vainikainen, and J. Takada, "Clusterization of measured DoA data in an urban macrocellular environment," COST 273 TD(03) 122, Paris, France, May 2003.

[13] K. Kalliola, H. Laitinen, P. Vainikainen, M. Toeltsch, J. Laurilla, and E. Bonek, "3-D double-directional radio channel characterization for urban macrocellular applications," *IEEE Trans. Antennas Propag.*, vol. 51, no. 11, pp. 3122–3133, Nov. 2003.

[14] P. Petrus, J. H. Reed, and T. S. Rappaport, "Effects of directional antennas at the base station on the Doppler spectrum," *IEEE Commun. Lett.*, vol. 1, no. 2, pp. 40–42, Mar. 1997.

[15] W. T. Ng and V. K. Dubey, "Comments on 'On the Doppler spectrum at the mobile unit employing a directional antenna,'" *IEEE Commun. Lett.*, vol. 6, no. 11, pp. 472–474, Nov. 2002.

[16] S. E. Foo, C. M. Tan, and M. A. Beach, "Spatial temporal characterization of UTRA FDD channels at the user equipment," in *Proc. IEEE Veh. Technol. Conf.—Spring*, 2003, vol. 2, pp. 793–797.

[17] B. D. Van Veen and K. M. Buckley, "Beamforming: A versatile approach to spatial filtering," *IEEE Acoust., Speech Signal Process. Mag.*, vol. 5, no. 2, pp. 4–24, Apr. 1988.

[18] K. Pedersen, P. E. Mogensen, and B. H. Fleury, "A stochastic model of the temporal and azimuthal dispersion seen at the base station in outdoor

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propagation environments," *IEEE Trans. Veh. Technol.*, vol. 49, no. 2, pp. 437–447, Mar. 2000.

[19] W. T. Ng and V. K. Dubey, "Effect of employing directional antennas on mobile OFDM system with time-varying channel," *IEEE Commun. Lett.*, vol. 7, no. 4, pp. 165–167, Apr. 2003.

[20] E. Baghdady, "Novel techniques for counteracting multipath interference effects in receiving systems," *IEEE J. Sel. Areas Commun.*, vol. 5, no. 2, pp. 274–285, Feb. 1987.

[21] *Digital Video Broadcasting (DVB); Framing Structure, Channel Coding, and Modulation for Digital Terrestrial Television (DVB-T)*, ETSI EN 300 744, 2001.

[22] J.-J. van de Beek, M. Sandell, and P. O. Borjesson, "ML estimation of time and frequency offset in OFDM systems," *IEEE Trans. Signal Process.*, vol. 45, no. 7, pp. 1800–1805, Jul. 1997.

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